

Effects of Glacial Meltwater in the GISS Coupled Atmosphere-Ocean Model: Part II: A Bi-polar Seesaw in Atlantic Deep Water Production.

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Abstract

The relationship between the Northern Hemisphere and Southern Hemisphere deep water circulation systems is explored in experiments with gradual and impulsive freshwater input through the St. Lawrence. With sufficient freshwater volume input (50 Sv years), North Atlantic Deep Water (NADW) cessation occurs, as does substantial cooling in the Northern Hemisphere. The colder temperatures are accompanied by increased mass and sea level pressure in the Northern Hemisphere, with corresponding lower pressure in the Southern Hemisphere. The low pressure response occurs at high Southern latitudes, consistent with the Antarctic Annular Mode, the leading mode of variability in the current climate. Stronger winds associated with this increased cyclonicity intensify the Antarctic Circumpolar Current, with heat flux divergences in the South Atlantic and convergences and warming in the Indian Ocean. Weddell Sea Bottom Water production increases in response to the South Atlantic high latitude cooling and sea ice growth, hence acting as a "seesaw" with the decreasing NADW, and even global Antarctic Bottom Water increases although not as strongly. The initial "seesaw" response occurs within a few years, although it takes some 100 years to maximize due to the response time of the ACC. The South Atlantic cooling occurs approximately in phase with North Atlantic, so the "seesaw" is not in temperature within that ocean basin; however, warming in portions of the Southern Indian Ocean occur out of phase with Northern Hemisphere cooling. NADW does not resume of its own accord once complete cessation occurs even when freshwater input is stopped, but when increased evaporation is used to force NADW formation temporarily, Weddell Sea Bottom Water decreases accordingly.

I. INTRODUCTION

In (Rind et al., 2001) (henceforth referred to as Part I) we described a series of experiments in which freshwater was added to the St. Lawrence. The greater the volume input, the greater the reduction in North Atlantic Deep Water (NADW) production. Broecker (1998) has suggested that Antarctic Bottom Water (AABW) changes may occur out of phase with NADW changes, due to the impact of the NADW circulation on the density structure in the Southern Ocean. The suggestion was motivated by several observations and interpretations. Firstly, Hugen et al. (1998) found that the ^{14}C content in atmospheric CO_2 increased by $\approx 50\%$ during the first 200 years of the Younger Dryas, and then steadily declined during the next 1000 years. Greenland ice core records do not indicate a gradual warming during this time period, so if the cooling on Greenland was associated with NADW cessation, it would imply NADW did not gradually resume. To find another way the excessive ^{14}C could be removed from the surface ocean, Broecker suggested that AABW increased, as occurred in the model experiments of Stocker and Wright (1996), Mikolajewicz (1998) and Schiller et al. (1998). The explanation for this increase is that without input of NADW at depth in the Southern Ocean, heat from the thermocline gradually mixes downward to the deep ocean, reducing its density, and allowing dense surface waters to penetrate to depth.

One consequence of this greater vertical mixing is that heat would be brought up from the depth, and perhaps lead to warming around Antarctica. This fits the second type of observation, that a pause in deglacial warming in the Byrd ice core on Antarctica occurred during the Bolling-Allerod warm interval (in the Northern Hemisphere); and that during the Younger Dryas cold interval (in the Northern Hemisphere and at southern latitudes as far south as New Zealand), Antarctica warmed (Jouzel et al. (1995)). To supply enough additional heat for warming, and to provide sufficient time to incorporate ^{14}C into the surface waters, Broecker suggested that greater transport occurred from lower latitudes (consistent with increased AABW production).

The suggestion assumes that the Greenland cooling of the Younger Dryas was produced by eliminating NADW production, the reality of which has come into question, as discussed in Part I. Furthermore, it has become apparent that Antarctica did not ubiquitously warm, as Taylor-Dome results show in-phase

cooling (Steig et al., 1998), although there may be some uncertainties associated with this result. We show below that as a result of NADW reduction in the model, warming occurred in the Indian Ocean, which is most likely to be picked up by Vostock.

As discussed below, the experiments performed in Part I show an unambiguous inverse relationship between NADW and AABW in the GISS coupled atmosphere-ocean model. Additional experiments were performed, in part to gauge the extent of this relationship, and they completely confirm the results. However, unlike Broecker's original suggestion, the connecting mechanism for this "seesaw" is through the atmosphere, not the ocean. It then allows the relationship to be extremely rapid, without the phase delay implied by the interpretation of the ^{14}C trends. Implications and consequences of these results will be given in the discussion section.

II. MODELING EXPERIMENTS

The first set of experiments used are those that were discussed in part I, and so will not be further described here. In addition, to emphasize the rapidity of the effect, a second set of experiments was performed. It has been suggested that a basic problem with experiments such as these used in Part I is that deglacial freshwater input occurs in massive pulses, rather than uniform values spread out for hundreds of years (Teller, 1995). The abrupt releases of water from proglacial Lake Agassiz during periods of lake level drawdown (Teller et al., 2000) provide a possible mechanism for periodic additional influxes of freshwater through the St. Lawrence Valley, Arctic Ocean, and Hudson Strait. On several occasions during deglaciation, up to 10 Sv may have been released to the oceans in a one year period, although the flux would have been less if drawdown occurred over several years. To test whether a large pulse of water over a short time would have any noticeable effect, and to address several additional questions, three additional experiments were performed. As indicated in Part I Table 2c, to completely eliminate in STAND the NADW production requires a volume of freshwater equivalent to ≈ 55 Sv years. Hence for the first extreme experiment, we added 10 Sv per year for 5 years to the St. Lawrence outflow, again input at 0°C . The run was then continued for another 195 years without any anomalous freshwater input. It will be referred to as the FRESHWATER PULSE experiment. A complete list of the new experiments is given in Table 1.

To test the mechanisms producing cooling in the North Atlantic, two modifications of this experiment were performed. In the first, the same freshwater input was added for 20 years (instead of 5) [called 20 YR FRESHWATER PULSE], and then run for another 20 years; and in the second, the same freshwater input was added for all 40 years [40 YR FRESHWATER PULSE].

To see if the relationship between NADW and AABW existed with greater NADW, and to explore whether a stable ocean state existed with such greater production, the reverse of the impulse experiment was conducted: evaporation from the North Atlantic at the latitude of the St. Lawrence was artificially increased by 10 Sv per year for five years. This will be referred to as the EVAPORATIVE PULSE experiment.

Finally, to explore the effects of increased evaporation in a situation where NADW production was dormant, a modified evaporation increase (5 Sv per year for five years) was implemented at year 200 of the FRESHWATER PULSE run. Freshwater loss of this magnitude is similar to that which occurred at the beginning of the last glacial epoch, some 115 thousand years ago, resulting in a drop of sea level of about 60 m in 5000 years (although it is not likely it came exclusively from the North Atlantic). This run is then called the MODIFIED EVAPORATIVE PULSE experiment.

III. RESULTS

A. Antarctic Bottom Water Response

The effect of freshwater input on NADW and AABW in the STAND control run and the experiment in which the St. Lawrence runoff was increased by $32\times$ (approximately 0.54 Sv input) is shown in Table 2. The Atlantic mass stream function, at a given latitude and vertical level, is defined for this paper to be the horizontal mass flux that enters the Atlantic basin north of the given latitude and beneath the given latitude. Thus the Atlantic mass stream function south of 36°S includes westerly mass flux south of Africa (and possibly easterly mass flux south of South America) in addition to the northerly mass flux of the desired latitude. Results are shown for the model's AABW in the South Atlantic as well as the global value. Due to its lack of complete stability, NADW production decreases by about 20% in the control run over the 160 year time period, but decreases by 100% in the $32\times$ St. Lawrence river-

flow experiment by 100 years, remaining negligible thereafter. AABW generated in the South Atlantic remains relatively constant with time in the control run, but increases by a factor of 3 in the $32\times$ St. Lawrence experiment. Global AABW decreases by 50% in the control run, but is relatively constant for much of the time period in the experiment. South Antarctic Bottom Water generation has clearly varied inversely with NADW production.

The streamfunction in the Atlantic is shown for the control run and the $32\times$ St. Lawrence experiment after 141–160 years in Figure 1. The disappearance of NADW and the invigoration of AABW production is evident.

The relationship between NADW and AABW in the different gradual freshwater input experiments is given in Table 3 for years 91–100. In general, the experiments with weaker NADW production have stronger AABW production by this time. Global AABW production is less affected.

Shown in Figure 2 is the result of the FRESHWATER PULSE experiment. As expected, the freshwater added during the 5 years was sufficient to eliminate production of NADW (Figure 2, top). Apparently, as long as the input occurs over a time-scale smaller than the oceanic mixing time of many hundred years, the effect is the same given a sufficient volume of freshwater forcing. Although the anomalous freshwater input was not added after year 5, NADW production did not return. AABW generation in the South Atlantic increased immediately, although the biggest gain took over 100 years to arise (Figure 2, middle). By that time, global AABW also had clearly increased (significant at the 99% level), although by a smaller magnitude (Figure 2, bottom).

B. Salinity Response

Given that freshwater is being added to the Northern Hemisphere, we can investigate how far anomalously low salinity had propagated by ≈ 150 years, the time shown in Figure 2. Shown in Figure 3 is the Atlantic salinity change. Reduced salinity is found throughout the North Atlantic, extending across the equator above 1200m, and as far south as 30°S above 400m. Higher salinity exists for the rest of the South Atlantic. Reduced upwelling in the southern tropics, associated with NADW removal, may be responsible for the decreased salinity at the surface, and the increased salinity below relative to the control run.

We can also refer to Figure 4 in Part I, which pro-

vides the global surface salinity change. By 141–160 years decreased salinity has affected the global from high northern latitudes to about 30°S in all ocean basins, with the strongest effect in the Atlantic, while little change or slight salinity increases are found further south.

From both of these presentations, we can conclude that the direct impact of the added freshwater is not contiguous with the region of AABW increase. Nor has the change in NADW provided a contiguous path of altered salinity at depth to high southern latitudes.

C. Temperature Response

Temperature change in the Atlantic for this time period is shown in Figure 4 for the 32× St. Lawrence experiment. The cold freshwater, and reduced poleward heat transport have cooled the North Atlantic. Reduced upwelling, however, has led to a large region of warming in the tropics and southern subtropics. Additional cooling can be found at high southern latitudes.

The Weddell Sea cooling is shown as a function of time in Figure 5 (top). Through the first 150 years, while freshwater was being added in the 32× St. Lawrence experiment, cooling gradually increased. In the realistic freshwater input experiment, LTC (1), there was little systematic effect. In conjunction with the cooling, sea ice increased in the 32× St. Lawrence experiment (Figure 5, middle), with little change in the LTC (1) experiment.

The global distribution of temperature change and sea ice response for the FRESHWATER IMPULSE experiment is shown in Figure 6, averaged over years 181–200 of the experiment, 176 years with no additional freshwater insertion and after 160 years with no NADW production. In each ocean basin, warming occurs in the southern subtropics to about 40°S, even further south in the Indian Ocean. Somewhat stronger cooling arises in the Weddell Sea region than in the other ocean basins at high southern latitudes. These results are generally similar to those shown for years 141–160 (60 years after NADW shutdown) in the 32× St. Lawrence experiment (Figure 6 of Part I.) indicating that they do not depend on how rapidly the deep water response occurs nor on the length of time after deep water has ceased, once a certain equilibrium is reached (i.e., the cooling did not appear to intensify with the additional 100 years of NADW cessation). The sea ice mass increases by 134 kg/m², and sea ice cover more than doubles, with strong longitudinal variability in the Southern Ocean. The in-

creased salinity at high southern latitudes in the 32× St. Lawrence experiment (and, as shown in Part I, Figure 3, not in the LTC(1) experiment) is at least partly the result of brine rejection accompanying the sea ice growth.

Increased surface salinity and colder surface temperatures both increase the density of the surface waters, and as both the temperature and salinity changes decrease with depth (Figures 3,4), they also increase the instability of the water column. These results are then consistent with increased AABW production.

D. Ocean Transport Response

Why is the temperature cooling in the South Atlantic? Broecker (1998) suggested that reduced inflow of warm NADW would influence the Southern Ocean region, but no contiguous temperature effect at depth from high northern to high southern latitudes is visible (Figure 4). However, shown in Figure 5 (bottom) is the change in ocean heat transport convergence into the Weddell Sea. While there is much variability, values are generally negative in the 32× St. Lawrence experiment, with little change in LTC(1). This result indicates that at least part of the cooling in the Weddell Sea is due to a reduction in ocean heat convergence into the region. Another, radiative, component is associated with the increased sea ice and hence greater reflectivity, as well as slight reductions in atmospheric water vapor absorption of longwave radiation (Table 4 of Part I).

The reduced convergence is unexpected, since increased AABW would be thought to provide for greater meridional heat advection to high southern latitudes. This in fact is the reasoning behind Broecker's (1998) assessment of what he thought was the out of phase relationship between Southern and Northern high latitudes during the Younger Dryas. Greater meridional heat advection is taking place. Figure 9 in Part I shows that greater southward (less northward) energy transport is occurring in the Atlantic. Figure 10 of Part I shows that this increased poleward heat flux is occurring in the western South Atlantic, consistent with increased bottom water production in the Weddell Sea. We reproduce the heat transport figure, this time from a Southern Hemisphere polar perspective, for the last 195 years in the FRESHWATER IMPULSE experiment in Figure 7; the results are completely consistent with those shown in Part I for the gradual freshwater increase experiment. Accompanying the latitudinal convergence of heat is a

longitudinal heat divergence, with little added heat coming into the South Atlantic at 65°W compared to the flux out at 20°E. In the FRESHWATER IMPULSE experiment, averaged over the 195 years of little or no NADW production, the heat flux divergence in the region of 44°S–80°S, 65°W–20°E amounted to 43×10^{13} W relative to control run values. At the same time, increased longitudinal heat flow into the Southern Indian Ocean is occurring, with relative heat convergence of 80×10^{13} W in the 44°S–72°S, 20°E–145°E. This additional heat is responsible for the warming seen at relatively high southern latitudes in that ocean basin (Figure 6; see also Figure 6 of Part I), overcoming in part the radiative cooling that affects the whole hemisphere. To understand why the longitudinal effects are occurring, we have to refer to the atmospheric circulation changes accompanying NADW production cessation.

E. Atmospheric (and coupled Oceanic) Response

As temperatures cool in the NH associated with the NADW cessation, due to decreased poleward oceanic heat advection and consequent sea ice growth, sea level pressure and atmospheric mass increase, as shown in Figure 8 for the $32 \times$ St. Lawrence experiment (top); note that this effect does not arise in LTC(1) (Figure 8, bottom), which had substantially less NADW change and consequent Northern Hemisphere cooling. The increased mass predominantly comes from the Southern Hemisphere, and in particular, mass decreases over the Southern Polar region, similar in a broad sense to the first EOF response in sea level or surface pressure, the "Antarctic Oscillation" or annular mode (Thompson and Wallace, 2000).

The realization of what in effect is a "high phase" of the Antarctic Oscillation is associated with the tropical warming that results from NADW reduction and reduced tropical upwelling (Fig. 4); the increased latitudinal temperature gradient away from the tropics provides for a west wind increase in the troposphere, with relative equatorial planetary wave propagation away from higher latitudes, as has been associated with the current high phase of the polar oscillations and tropical warming from increased CO₂ (Shindell et al., 1999). Equatorward planetary wave propagation transports angular momentum toward the pole as shown in Figure 9 (the "advection" term). Increased angular momentum at high latitudes, providing for a more west to east wind flow, is then asso-

ciated with greater cyclonicity and lower atmospheric pressure.

The reduction in sea level pressure at high Southern Latitudes led to the increased west winds in the circumpolar region. This has the effect of driving an intensified circumpolar current; this can be seen as the increased loss of angular momentum by surface drag ("surface") for the latitudes of the Southern Ocean in Figure 9. That such an intensified current occurs throughout the Southern Ocean can be seen in Figure 11 of Part I. We show in Figure 10 for the FRESHWATER IMPULSE experiment the change with time of the surface pressure, averaged over the region 60–90°S, and the Antarctic Circumpolar Current (ACC) magnitude as calculated through the Drake Passage. The ACC is the result of an equilibrium balance between surface wind stress forcing and bottom drag; it takes some 50 years for the pressure drop to reach a relatively stable value, and an additional 30 years for the ACC to do so. It is only after this time that cooling strengthens in the Weddell Sea, and AABW changes maximize. It is due to the continental configuration (the relative closeness of South America to Antarctica, compared with South Africa), that the intensified current leads to longitudinal energy transport divergence out of the South Atlantic. The processes are highly interactive: the cooling of the South Atlantic with a consequent increase in latitudinal temperature gradient helps generate added eddy energy; this added eddy energy helps provide added momentum transport to intensify west winds and low pressure at the high southern latitudes, when then helps provide for the South Atlantic cooling through its effect on the ACC and longitudinal heat transport divergence.

F. Additional Pulse Experiments

Since the atmospheric mass-transfer mechanism depicted in this model depends upon Northern Hemisphere cooling, it is instructive to understand why this cooling is taking place. As indicated in Part I, a 50% reduction in poleward heat transport convergence at high latitudes in the North Atlantic produces some of the cooling, and it is amplified radiatively by the growth of sea ice. In the FRESHWATER IMPULSE experiment, the cooling over Greenland reached 3°C after 40 years, gradually increasing to 4°C before stabilizing; note NADW reduction to near zero occurred after 20 years, as did the 50% reduction in converged heat transport. When we allowed the freshwater input to continue at its high

rate for 20 years before ceasing [20 YR FRESHWATER PULSE], NADW production again went to near zero after 20 years, and the heat convergence again dropped 50%, but now temperatures reached the 3°C cooling magnitude in just 20 years (Table 4). When freshwater input was continued for 40 years [40 YR FRESHWATER PULSE] converged ocean heat transport originally declined even further, but eventually stabilized at the 50% reduction, while the temperature over Greenland was reduced by 6°C. Apparently half the cooling was associated with the freshwater input itself of 0°C water, and the other half with the NADW cessation. As noted in Part I, this model produced greater cooling than arose in the simulations of Manabe and Stouffer (2000), perhaps because this input of cold water was not occurring in their study.

With greater cooling in the Northern Hemisphere, greater mass buildup is expected, and AABW increase should be greater. The results after 20 years in 20 YR FRESHWATER PULSE, and after 40 years in 40 YR FRESHWATER PULSE are shown in Table 4. South Atlantic AABW changes are greater as the cooling expands (Greenland is not a perfect indicator of the Atlantic basin and hemisphere temperature change but it is indicative).

If this process works for NADW reduction and consequent Northern Hemisphere cooling, it should also be applicable for NADW increases and Northern Hemisphere warming. The EVAPORATIVE PULSE and its modification experiments were an attempt to produce the inverse of the FRESHWATER PULSE experiments. They were also an attempt to determine if another stable mode of operation existed in the ocean, at least in the GISS model.

In the EVAPORATIVE PULSE experiment, the increased evaporation for the first five years did indeed result in an increase in NADW production. With this forcing, NADW production tripled during the course of the five years, accompanied by warming in Greenland, and South Atlantic AABW simultaneously disappeared entirely (Table 4). The relationship was therefore as expected.

In the MODIFIED EVAPORATIVE PULSE experiment, 5 Sv per year was removed for five years through added evaporation starting from year 200 of the FRESHWATER PULSE simulation with no NADW production. NADW production was re-invigorated, rising to values somewhat greater than in the control run for a little more than five years, and Greenland temperatures warmed back to control run values. During that time, South Atlantic AABW decreased to

close to its control run value (from the larger values shown in Figure 1). This experiment was also an attempt to determine whether dormant NADW could have been revived with such a perturbation. In fact, NADW could not be maintained, but it did not subsequently disappear entirely, stabilizing at about 4 Sv for the next century. This is an interesting result in itself, and implies that NADW could be reinitiated in the model at least to a minor extent with a sufficiently large perturbation, stabilizing at a small but non-zero level (similar to the magnitude produced by freshwater in the Manabe and Stouffer (2000) experiment). AABW also did not return to its previous high value, and cooling in Greenland (and elsewhere) was not as extensive. These experiments help verify that the relationship between deep water formation in the two hemispheres does appear to be out-of-phase with little time lag, at least when associated with strong freshwater/salinity perturbations.

DISCUSSION

Superficially, these experiments are in accord with Broecker's (1998) suggestion of a bipolar seesaw in AABW production, especially in the Atlantic. Given that the mechanism acts through the atmosphere it is extremely rapid, with an initial AABW increase in the Weddell Sea essentially synchronous with reduced NADW production. As shown in Figure 2, global AABW is static for about 50 years after NADW cessation, but then starts increasing, which would then begin to draw down ^{14}C from its peak values. In the FRESHWATER IMPULSE experiment, AABW increase maximizes some 125 years after NADW production first goes to zero, both in the South Atlantic and globally. Past this time, there is little further change (Figure 2), in apparent disagreement with the observations noted in the introduction which found a continual decline in ^{14}C for 1000 years. Even more significantly, the temperature change in the South Atlantic cools when sufficient NADW reduction is in place, rather than warming as Broecker suggested. [In the experiments discussed in Part I, cooling at high southern latitudes is clearly visible with a 90% NADW reduction (in years 80–100 of $32\times$ St. Lawrence); with a 70% decline (years 40–60) it is not yet robust.] As also noted in the introduction, observations now imply that cooling was not ubiquitous over Antarctica; in the model experiments, the heat divergence out of the South Atlantic is accompanied by heat convergence in the Indian Ocean, implying some degree of heterogeneity in temperature

response. The increased poleward transport hypothesized by Broecker to explain the added ^{14}C uptake of surface waters does occur in the western South Atlantic (as implied by the heat transport change in Figure 7 and by the ocean current change in Part I, Figure 11).

In comparison with results from other experiments, Schiller et al. (1997) found that after several hundred years of freshwater input, NADW advection south of 30°S eventually ceased, and AABW gradually expanded; by the end of their experiment, AABW increased by 15% (with a streamfunction value of 9 Sv). The pattern was not in steady state, and overall AABW and Southern Ocean convection were not significantly affected. The use of large flux corrections in this region might have influenced their result. Manabe and Stouffer (2000) do not indicate any change in AABW, only that 500 years after NADW weakening, AABW eventually extends considerably north of the equator in the Atlantic. They do, however, report cooling at high latitudes in the Southern Ocean of a similar magnitude to those shown in Figure 5.

Of course, we cannot ignore the more general question of whether these results have any relevance to the Younger Dryas itself. As noted in Part I, substantial questions remain as to whether the Younger Dryas cooling did in fact result from a rapid shutdown in NADW driven by freshwater input. When the estimated realistic freshwater is added in the model (of order 0.1–0.2 Sv), the NADW response appears to be too slow. Nevertheless, even under these circumstances the bipolar oscillation occurs, although all changes are much more gradual.

The model results suggest specific responses that could be tested in the paleodata. AAC increases should accompany decreased NADW production, although with a lag of a few decades; temperature changes around Antarctica in response to the effect could be of varying sign with longitude, as has already been observed; and while AABW production in the South Atlantic should have increased nearly simultaneously with NADW reduction, global AABW production should be much less affected. The results also have ramifications for deep water nutrient proxies such as $\delta^{13}\text{C}$ and Cd/Ca measurements of benthic foraminifera, which are used to assess NADW changes with time, and which assume AABW in the Atlantic is unchanged. Were Atlantic AABW to have increased, then the presumed NADW changes would have been less (i.e., NADW would not have decreased as strongly). This would then be more consistent with

the estimates of realistic freshwater input.

CONCLUSIONS

The primary conclusion from this work is that AABW production in the Weddell Sea varies inversely with NADW production, producing a "bipolar" seesaw. This occurs via an atmospheric teleconnection, whereby mass increases in the Northern Hemisphere and decreases in the Southern Hemisphere (Antarctica), increasing the AAC current and longitudinal heat flux divergence out of the South Atlantic, with cooling and sea ice growth/salinity increases amplifying bottom water production. As longitudinal differences in heating/cooling arise in the Southern Ocean, global AABW shows less change but still increases. To the extent that the results are relevant for the Younger Dryas, they are somewhat inconsistent with explanations for the observed ^{14}C behavior during the deglaciation; although increased Southern Ocean bottom water would have helped ^{14}C levels to decline to normal values, it appears the effect would have been more rapid than the ≈ 200 years implied by the data. The results also do not suggest an out-of-phase temperature relationship between high latitudes of the two hemispheres in the Atlantic, but do imply the possibility for heterogeneity in the longitudinal temperature response around Antarctica.

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Table 1. Additional experiments performed with STAND in which freshwater pulses or evaporative pulses are applied.

NAME	DESCRIPTION
FRESHWATER PULSE	Addition of 10 Sv per year for five years through the St. Lawrence followed by 195 year simulation
20 YR FRESHWATER PULSE	Addition of 10 Sv per year for 20 years, followed by an additional 20 year simulation
40 YR FRESHWATER PULSE	Addition of 10 Sv per year for 40 years
EVAPORATIVE PULSE	Added evaporation of 10 Sv per year for five years throughout the North Atlantic at the latitude of the St. Lawrence followed by 115 year simulation
MODIFIED EVAPORATIVE PULSE	Added evaporation of 5 Sv per year for five years throughout the North Atlantic at the latitude of the St. Lawrence followed by 95 year simulation. Started year 201 of the FRESHWATER PULSE simulation

Table 2. Antarctic Bottom Water mass stream function (Sv) as a function of time in the control run (STAND) and the 32× St. Lawrence experiment. Results are shown for both the Atlantic and Global Southern Ocean. Also shown is the stream function associated with NADW.

YEAR	6–10	21–25	46–50	71–75	96–100	116–120	136–140	156–160
SOUTH ATLANTIC (68°S)								
Control	12.22	11.34	13.40	11.38	14.14	13.18	12.84	10.46
32× St. Lawrence	8.76	13.54	14.64	16.36	19.62	25.46	27.52	26.62
GLOBAL (68°S)								
Control	18.28	17.58	16.78	14.5	15.0	12.02	11.48	9.98
32× St. Lawrence	16.92	16.3	17.3	16.04	14.32	15.74	15.78	12.96
NORTH ATLANTIC (52°N)								
Control	22.22	21.3	19.85	18.8	19.47	19.57	17.1	15.34
32× St. Lawrence	20.1	13.56	6.3	1.98	1.0	-0.84	-0.3	-0.3

Table 3. Antarctic Bottom Water stream function (Sv) in the different experiments in STAND for years 91–100 in the South Atlantic and Global Southern Ocean, as well as NADW values.

	AABW		NADW
	Atlantic	Global	
Control	13.0	14.6	19.5
2× St. Law.	12.9	17.5	18.4
4× St. Law.	14.3	15.3	17.6
8× St. Law.	15.7	17.2	13.2
32× St. Law.	18.6	14.6	1.0
LTC (1)	13.3	14.7	16.3

Table 4. North (50°N) and South Atlantic (66°S) Bottom Water changes in the additional PULSE experiments. Also given is the surface air temperature change over Greenland.

	YEAR	GREENLAND SURF TEMP (°C)	NADW (SV)	ATL AABW (SV)
Control		NA	15–20	-13
FRESHWATER PULSE	20	-1	3	-18
20 YR FRESHWATER PULSE	20	-3	2	-35
40 YR FRESHWATER PULSE	40	-6	0	-47
EVAPORATIVE PULSE	5	+2	69	0
FRESHWATER PULSE	200	-3	0	-18
MODIFIED EVAPORATIVE PULSE	205	0	30	-12
MODIFIED EVAPORATIVE PULSE	300	-2	4	-14

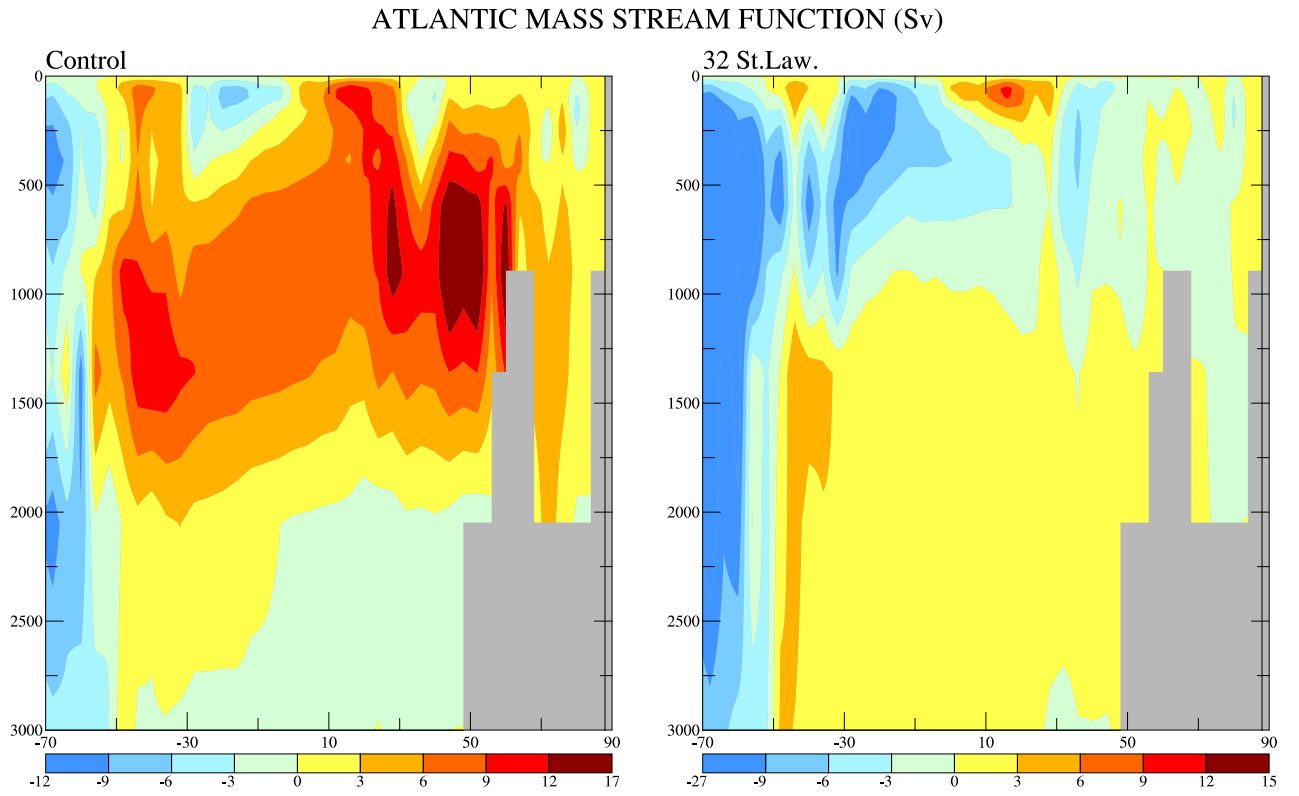


Figure 1. Atlantic mass streamfunction (Sv) in the control (left) and 32×St.Lawrence experiment for years 141–160 (right). Positive values represent clockwise rotation in the plane of the figure.

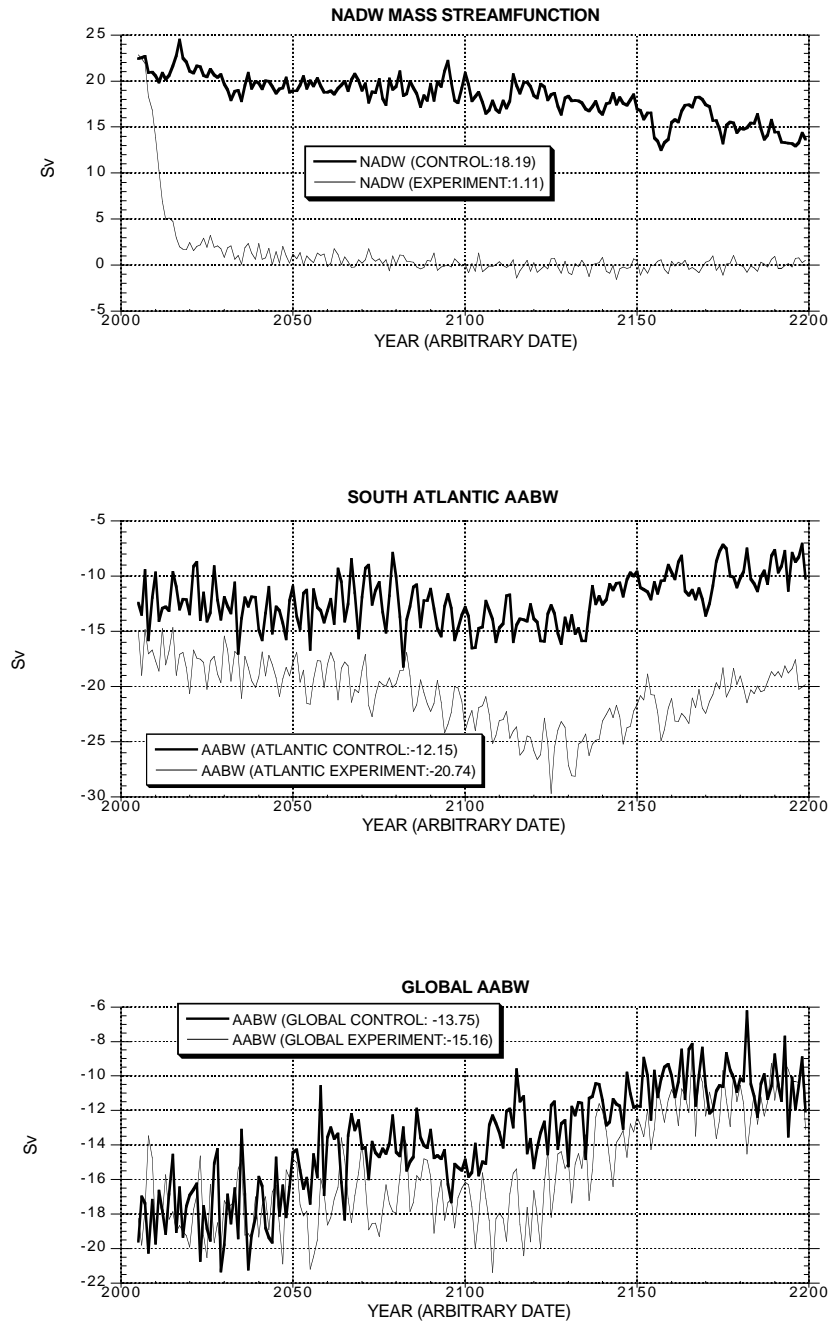


Figure 2. Line graph showing both the control and the experiment of NADW, South Atlantic (Weddell Sea) AABW, and global AABW for 195 years (the first five years when freshwater was being added are omitted) in the FRESHWATER PULSE experiment. Stream function values for the NADW were calculated at 52°N, 900m, while for AABW, maximum values from 64–68°S were used. Averaged values over the time period are shown in parenthesis.

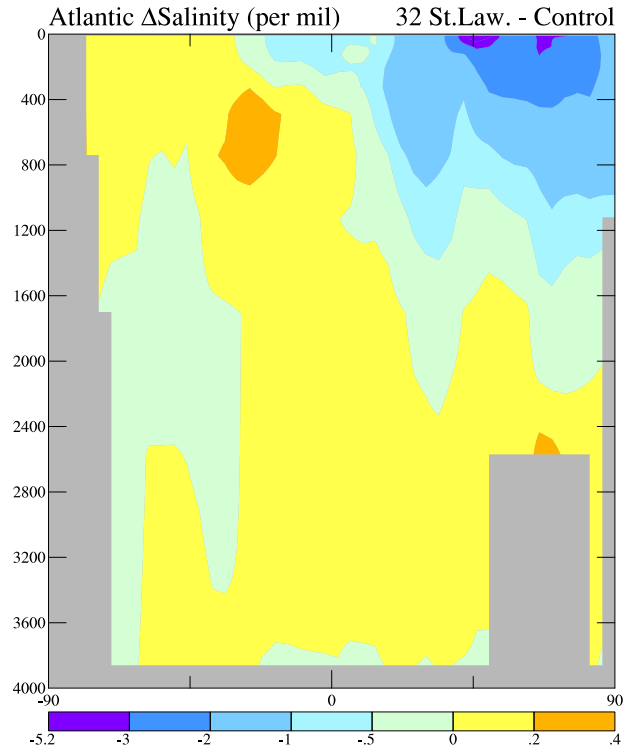


Figure 3. Ocean salinity change as a function of latitude and depth between the 32 \times St. Law. experiment and the control for years 141–160.

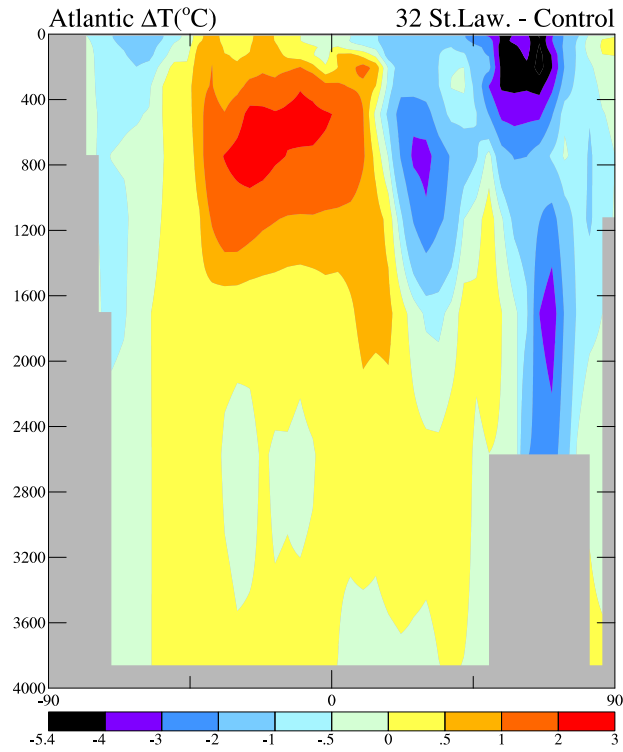


Figure 4. As in Fig. 3 except for temperature.

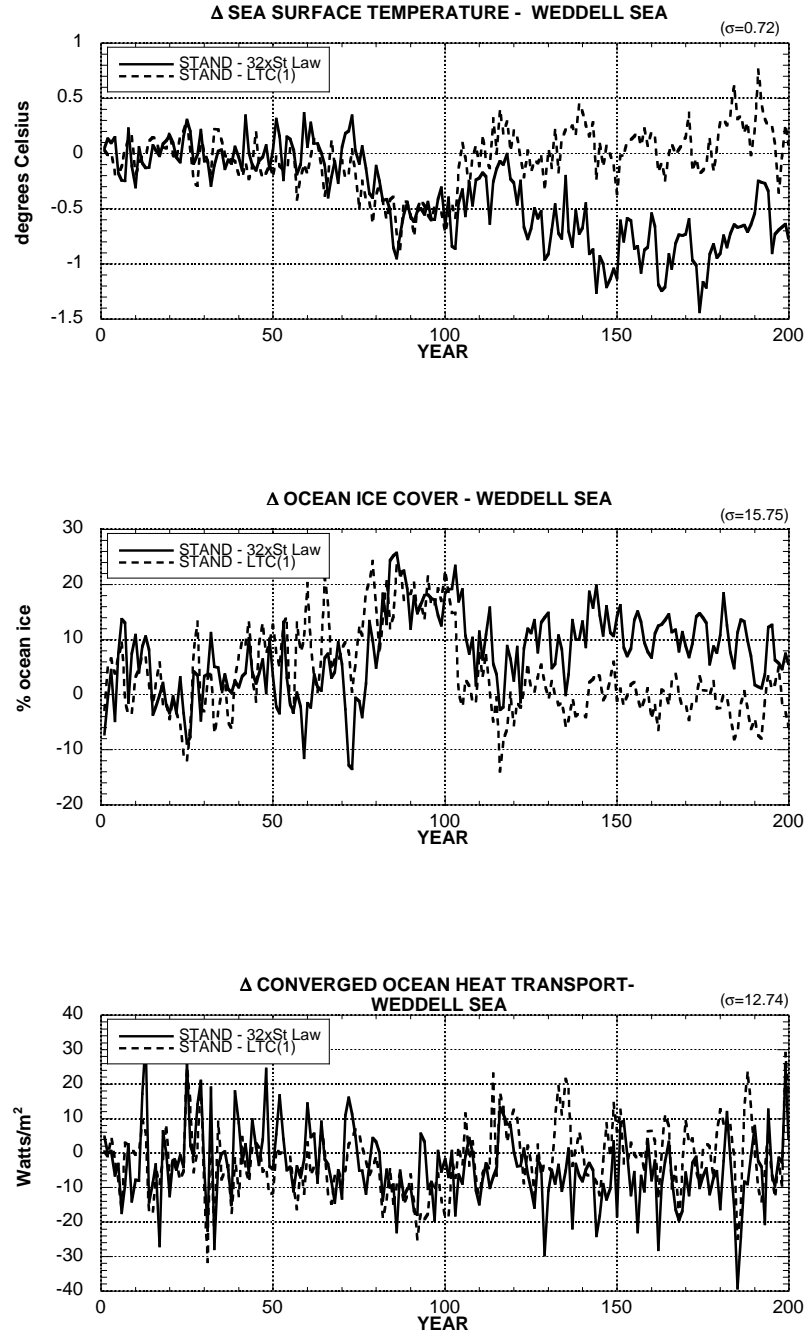


Figure 5. Sea surface temperature change (top), change in converged ocean heat transport (middle) and change in ocean ice coverage (bottom) for the Weddell Sea as a function of time in the $32 \times \text{St. Law.}$ and LTC(1) experiments. Note that freshwater input is ended in year 160, as discussed in Part I.

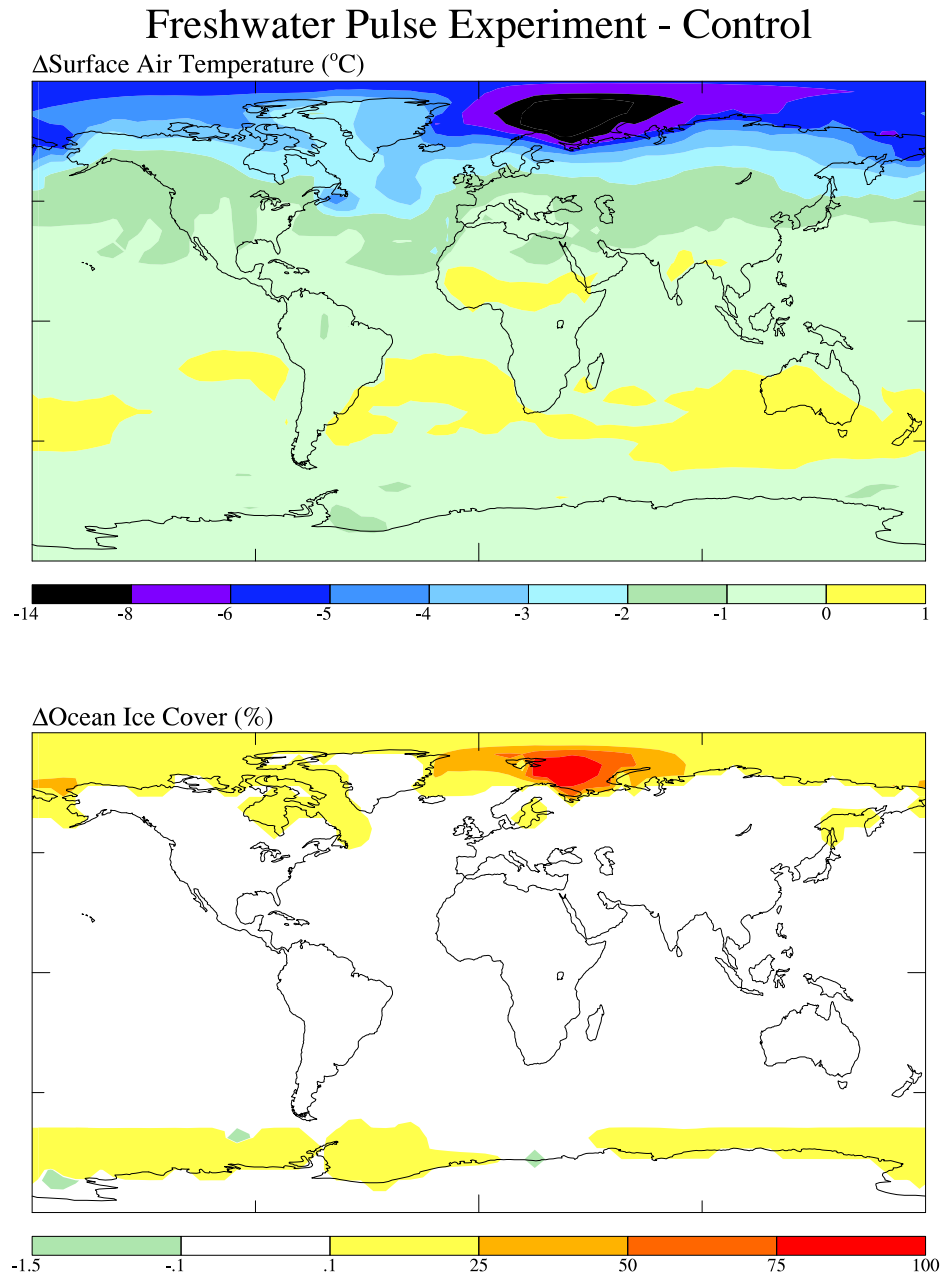


Figure 6. Change in annual surface air temperature (top) and sea ice (bottom) between the FRESHWATER IMPULSE experiment and the control averaged over 20 years, after 175 years of no NADW production.

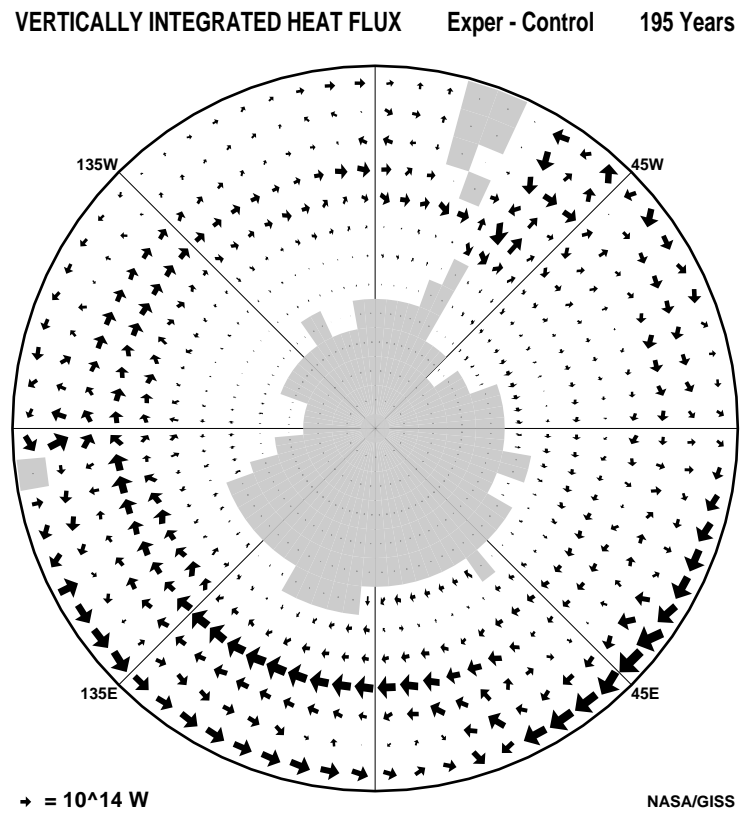


Figure 7. Change in vertically-integrated oceanic heat (potential enthalpy) advection for the last 100 years of the FRESHWATER IMPULSE experiment. The scale is given on the figure.

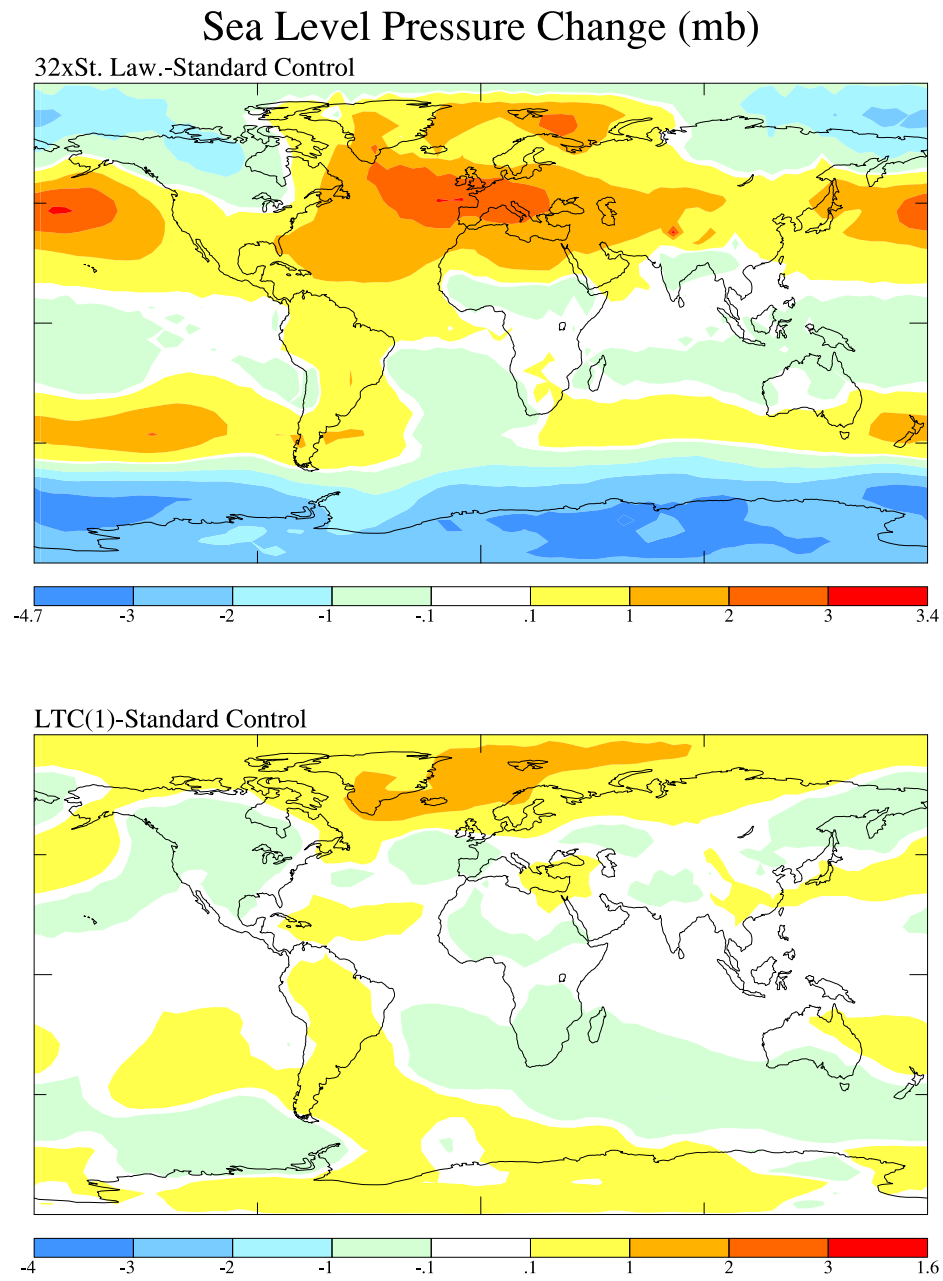


Figure 8. Sea level pressure change (mb) for years 141–160 in the 32× St. Law. run (top) and LTC(1) (bottom).

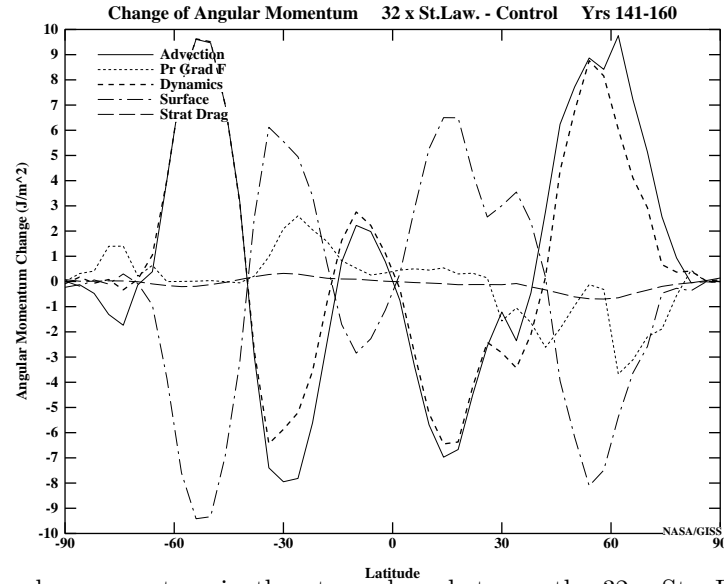


Figure 9. Change of angular momentum in the atmosphere between the $32\times$ St. Law. run and the control for years 141–160. Vertically integrated values are shown for the difference in atmospheric dynamics (the sum of changes in advection due to mean circulation and eddy effects, and the pressure gradient force from flow over orography), surface drag, and stratospheric drag.

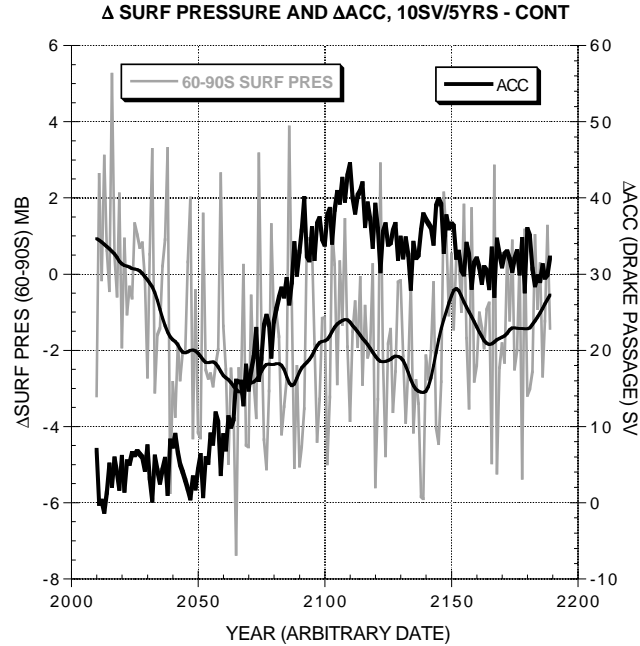


Figure 10. Line graph of the change in surface pressure at high southern latitudes, averaged over $60\text{--}90^\circ\text{S}$, and the Antarctic Circumpolar Current through the Drake Passage, FRESHWATER PULSE experiment minus control. Control values used for the comparison employ a 21 year running mean. The smoothing applied to the surface pressure curve uses a local weighted least squared fit with 10% of the data considered during smoothing.